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Stress Analysis to Improve Pitting Resistance in Gear Teeth

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Abstract

Helical gears are subjected to contact fatigue loads, which may result in the damage of the gear teeth, for example by pitting-type failure. Microstructural features, mechanical properties and residual stresses have strong influence on the pitting resistance of the material. Case hardening, followed by shot peening processes, are usually carried out to produce a wear-resistant surface with compressive residual stresses established in the gear tooth surface region. This work aims to evaluate, by finite element analyses, the stress distribution through the gear teeth during the gear coupling. The results allow the evaluation of the stress components that may lead to the pitting failure, indicating the design variables that are important to improve the reliability of the gear.

Keywords: gears; contact induced failure; Finite Element Method; nano-indentation; microstruture

1. Introduction

One of the most important types of failure in gear is the contact fatigue [1]. The contact fatigue results from a Hertzian stress state, in which the maximum pressure is established at the center of the contact due to two common assumptions: a) circular, elliptical or line contact surface area between curved tooth surfaces and, b) parabolic pressure distribution. A hydrostatic component occurs in the subsurface state of stress, which inhibits tensile fracture. The development of carbon profiles in steel case hardening, and the generation of compressive residual stresses are solutions to improve the resistance to pitting-type damage to gear tooth [1].

Improved mechanical properties, wear and fatigue resistances can be obtained by conducting different manufacturing processes. Approaches were made based on hardness and residual stress profiles in the gear tooth, the microstructural features, the shot peening parameters [2], the residual stresses [3,4] and the case depth [5]. Nevertheless, the hardness and the residual stresses are hard to be measured and present a wide range of values.

The effect of residual stresses in the tooth subsurface fatigue fracture was analyzed [6], in which the crack is initiated due to the combined action of the alternating stresses from the idler usage of the gear and the residual stresses. In addition, numerical and experimental analyses were conducted to evaluate material parameters affecting gear tooth [7,8].

This work deals with the evaluation of stress simulation throughout the contact gear teeth and its relation with material hardness profile and the residual stress. A gear, presenting a carbonitrided surface was characterized by nano-indetation, Vickers micro-hardness and X-ray diffraction methods. These results were applied to the finite element method (FEM) models, which allowed the assessment of the stresses developed during the contact between a pair of helical gears and provided information about the failure of the gears.

2. Experimental and Numerical Procedures

Microstructural characterization and mechanical properties measurements are evaluated based on a gear made of 17NiCrMo7 steel, in which carbonitriding and shot peening manufacturing process were carried out.

The microstructure of the section of a helical gear tooth is characterized by scanning electron microscopy (SEM) after metallographic sample preparation, which consisted on grinding and polishing up to 1 μm. Further, the sample was

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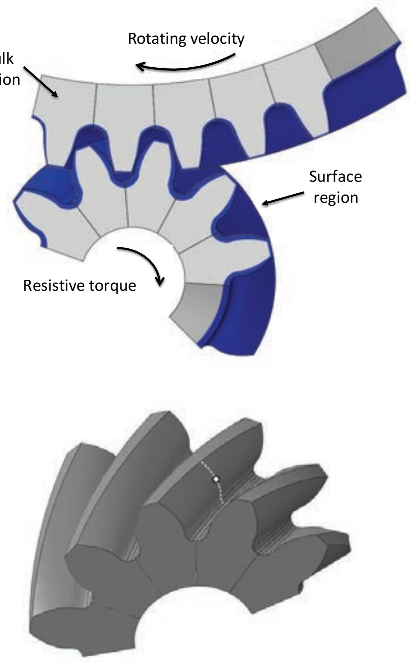
etched, with Nital (3% HNO_3), to reveal microstructural features. X-ray diffraction (CuKα radiation) was run up to a depth of 30 μm, allowing the estimation of planar residual stresses based on peak shift measurements.

The micro hardness profile is measured by Vickers technique with 1 kgf load. Nano-hardness profile is measured using Hysitron TI950 nano-indentation system. In this case, the Berkovich tip and an indentation load of 3 mN is used. The profile is measured by 50 μm equally spaced indentations up to a total depth of 1,600 μm. Hardness and Young's modulus are calculated using the Oliver and Pharr method [9].

The numerical model of a not used, no load condition, helical gear is generated and simulated in the Abaqus v6.13 simulation package. In this model, five pairs of gear teeth (Fig. 1a) are considered and the numerical equations are solved using an explicit algorithm. Each gear tooth is discretized by 8,128 linear hexahedral elements and presented two distinct regions: near surface (blue) and bulk (light gray) regions in Fig. 1a.



a)

b)

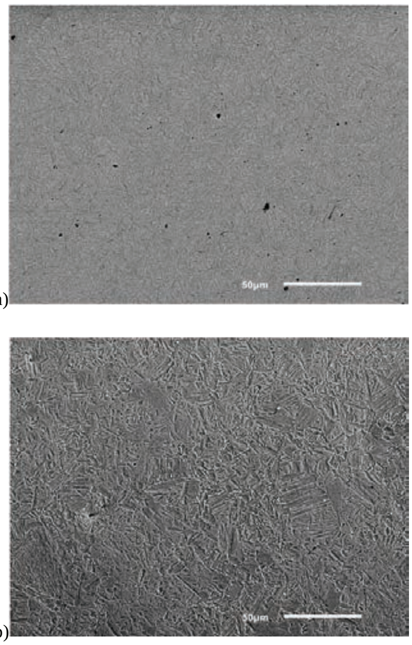
Fig. 1 – Finite Element Model of the helical gears: a) numerical model of five pairs of helical gear tooth, in which blue indicates the near surface region while the light gray indicates the bulk region of gear teeth; b) central point and path of numerical results extraction.

The near surface region, defined by a thickness of 500 μm from the surface towards the inner region, is discretized by a minimum of 3 elements in thickness to better capture the contact induced stresses. Near surface and bulk mechanical properties are obtained by nano-indentation technique. Three levels of compressive residual stresses (0.5 GPa, 1.0 GPa, and 2.0 GPa) are analyzed for the near surface region.

A general contact algorithm with a dry coefficient of friction of 0.1 is applied to the model. Boundary conditions consisted of a resistive momentum of 136 kNmm applied to the lower (driven) gear and a constant rotational velocity of 1.0 rad/s applied to the upper (driver) gear. All other degrees of freedom are constrained, allowing only movements in transversal plane of the gears.

3. Results and Discussion

SEM image of the transversal section of the gear shows a inner region (Fig. 2a) that transitions to a martensitic phase in the near surface region (Fig. 2b), produced by carbonitriding and shot peening processes. The residual stress in the near surface region, measured by the X-ray diffraction technique, resulted in a compressive value in the range of 550 MPa to 580 MPa. The hardness profile obtained by Vickers micro-hardness and nano-indentation is presented in Fig. 3, which shows good agreement between measurements.



a)

b)

Fig. 2 – Back scattering SEM image of the microstructure of one gear tooth: a) bainitic inner region and b) martensitic surface region.

The measured Young's modulus of near surface and bulk regions are 200.7 GPa and 187.9 GPa, respectively. The yield stress of those regions are estimated as 1/3 of the hardness profile of Fig. 3.

Numerical results allow the observation of the contact region between the gears, as displayed in Fig. 4a. This figure represents the instant of maximum contact stress at the selected point of Fig. 1b.

For helical gears, three pairs of gear teeth are always in contact. The contact pressure evolution for the selected point of Fig. 1b is presented in Fig. 4b. Cases with different levels of residual stress presented similar contact pressures, indicating that this variable does not influence the contact pressure distribution.

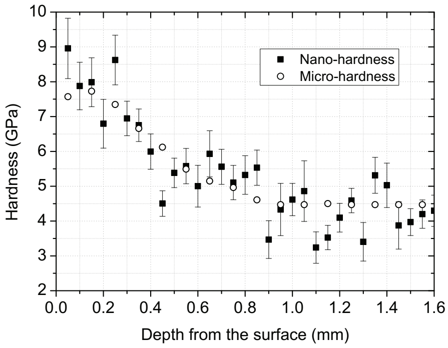


Fig. 3 – Hardness profile from surface towards the inner region of the helical gear measured by micro and nano-indentation techniques.

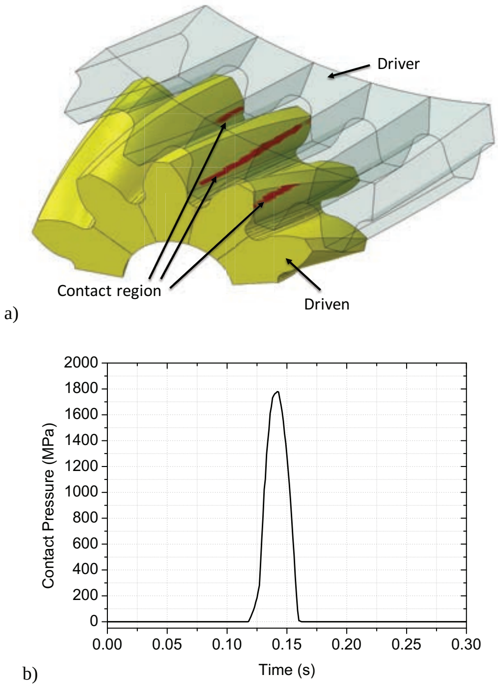


Fig. 4 – Contact in an engaged helical gear pair: a) contact region distributed in three pairs of gear tooth (red region) and b) evolution of contact pressure in the central point of the gear tooth (Fig. 1b).

Figure 5 shows the Von Mises equivalent stress and the stress amplification factor, which presents the ratio of stresses between the conditions with and without residual stresses, both on the tooth surface. In this figure, the dark gray region indicates the contact region between the gears for the instant of 0.145s.

For ductile materials, Von Mises criterion indicate regions in which plastic deformation may occur, leading to the failure of the material. Figure 5a indicates two regions with elevated stresses: the top edge of the teeth and at the contact region. The higher stresses at the top of the teeth are expected, since this region is more prone to wear due to the narrow shape. Also, higher stresses are expected at the contact region, which is the region that supports all contact loads. In this figure, the increase in the residual stress level allowed a reduction of the Von Mises based stresses at the contact region and an increase of the stresses outside the contact region. Figure 5b shows the amplification factor for the Von Mises equivalent stress. In this figure, two regions (both x=0.25 and x=0.68 normalized positions) present amplification of the Von Mises based stresses while the contact region shows a reduction of the stresses (detail of Fig. 5b) with the increase of the residual stress level.

The increase of the Von Mises based stress occurs due to the increase of the absolute value of the residual stress level. This may indicate regions more prone for crack nucleation based on the plastic deformation of the material instead of mode I failure.

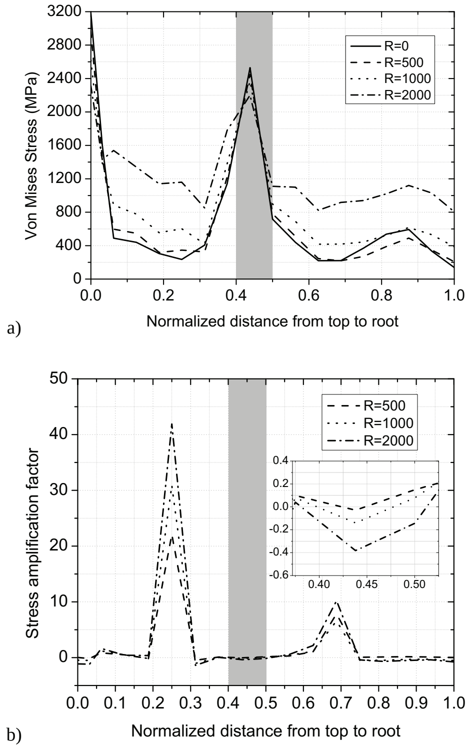
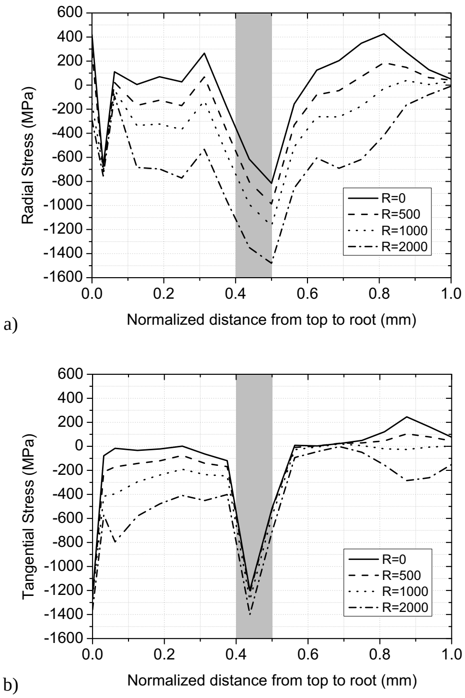


Fig. 5 – Stress distribution on the central gear tooth: a) Stress based on Von Mises criterion and b) Stress amplification factor due to the increase of the residual stress levels. Dark gray region indicates the contact region between the gears at instant 0.145s.

Radial stresses along the surface path, presented in Fig. 6a, are consistently lower for the case with higher compressive residual stresses. This suggests a lower tendency for surface pitting once surface cracks are nucleated, because a lower radial stress would reduce subsurface crack propagation based on mode I failure. In addition, higher compressive residual stresses promote lower tangential stress distribution (Fig. 6b) on the surface path of the gear tooth.

Normalized positions higher than 0.8 (region at the root of the tooth) present a transition from tractive to compressive tangential stresses with the increase of the compressive residual stresses, which may improve fatigue resistance of this region.



a)

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Fig. 6 – Stress distribution on the central gear tooth: a) radial and b) tangential stress distributions. Dark gray region indicates the contact region between the gears at instant 0.145s.

4. Conclusions

In this work, a pair of helical gear teeth were characterized by SEM, X-ray diffraction, Vickers micro-hardness and nano-indentation techniques, allowing the evaluation of material mechanical properties and residual stress. These mechanical properties and four residual stress levels were analyzed in the numerical models, leading to the following conclusions:

- The carbonitrided layer at the surface of the tooth presented 2.5 times the hardness of the bulk region, measured both by Vickers micro-hardness and nano-indentation techniques;
- The shot peening process produced a hardened region with 600 μm in thickness and a compressive residual stress of 550 MPa to 580 MPa;
- The increase in the compressive residual stresses allowed the reduction of the Von Mises, radial and tangential stresses at the contact region, leading to a improvement on pitting resistance at the surface of the tooth;
- The increase of the Von Mises based stresses at regions apart from the contact region may promote crack nucleation based on plastic deformation of the material;
- The transition from tensile to compressive tangential stresses at the root of the tooth with the increase of residual stresses may improve fatigue resistance of this region;
- Optimization of different microstructures or the thickness of the modified surface region can improve the resistance of the gear to pitting induced failure;
- Numerical results could improve material design as well as the evaluation of residual stress ranges that could improve gear lifetime.

Acknowledgements

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